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Assessment of Soil Susceptibility to Compaction Using Soil and Climatic Data Bases[1]

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ABSTRACT

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Owing to a wide range of soil types, climatic conditions and crop species, it its impossible to make a quantitative general statement about the effects that agricultural wheel traffic can have on soil compaction and plant response. There is a need to develop a methodology to assess the susceptibility of a given soil to compact and to predict the subsequent plant response. This paper outlines one approach being developed in the United States, using basic soil mechanics theory, soil survey data, long-term climatic data bases, and field research results.

INTRODUCTION

Soil compaction from wheel traffic of modern machinery is an increasing world-wide concern. Soil compaction has been identified as one of the leading causes of soil degradation threatening future productivity of American farm land. Compaction has the potential to affect crop growth and production directly, and also indirectly by increasing soil erosion and/or water runoff.

Owing to a unique combination of soil, climate and cultural practices, some regions of the United States have clearly defined compaction problems. For example, in the southeastern U.S., many soils are low in organic matter, contain non-swelling clays, are subjected to high rainfall amounts, do not go through cycles of freezing and thawing, and often support crops that require numerous field operations for seedbed preparation and pest control in addition to the normal planting and harvest operations (McKibben, 1971). As a result, hardpans develop that persist over seasons and often reduce yields significantly. In

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1971, it was estimated that in the southern United States crop yields were reduced by 10% because of soil compaction (Gill, 1971).

However, in the majority of the U.S.A., the consequences of soil compaction are not so clearly quantified. While crop yields may sometimes be significantly decreased by excessive compaction, Voorhees et al. (1985b) have also shown significant yield increases for wheat (*Triticum aestivum*) and soya beans (*Glycine max*) under moderate compaction in the soil–climatic regimes of the north central United States. Similar increases in crop yield with moderate compaction have been documented in Sweden (Eriksson et al., 1974) and Denmark (Rasmussen, 1976). Yield increases under moderate compaction are usually observed during relatively dry growing seasons, and are attributed to better germination and more efficient use of a limited water supply.

These cited examples of diverse crop response to compaction caused by wheel traffic underscore the complexity of the problem. Furthermore, the United States is diverse, in respect to both soil and climate, with 9 of the 10 soil orders (Anon., 1960) being represented in the contiguous U.S. Annual precipitation on farm land ranges from <250 mm to >1500 mm, with the frost-free growing season ranging from <90 days to >240 days. This precludes a general statement of compaction effect that pertains to all combinations of soils, crops and climates. Thus, an assessment scheme is needed that not only addresses the soil mechanics response to a compactive force, but also assesses subsequent crop growth response to that soil condition. The scheme proposed in this paper for assessing the susceptibility of soil to compaction is based on the premise that (1) all soils will not respond to a given compactive force in the same manner or extent, and (2) all crops will not respond in the same way to a given physical soil environment; crop reaction also depends on the climatic regime under which it is growing.

The first premise has been well documented; the second is not so well understood but is extremely important. The object of this paper is to outline briefly one approach being taken by soil scientists in the United States, with examples of progress where appropriate. Basically, three steps are involved, each building on the one before: (i) determination of soil compactibility; (ii) assessment of compaction probability; (iii) estimation of agro-economic response to compaction.

SOIL COMPACTIBILITY

Depending on the desired degree of sensitivity, several methods are available for measuring and/or estimating a soil's response to a compactive force. Larson et al. (1980) suggested that agricultural soils could be grouped into four categories based on the shape of the virgin compression curves (Fig. 1). Thus, as a first approximation, soil compactibility can be categorized based on type of

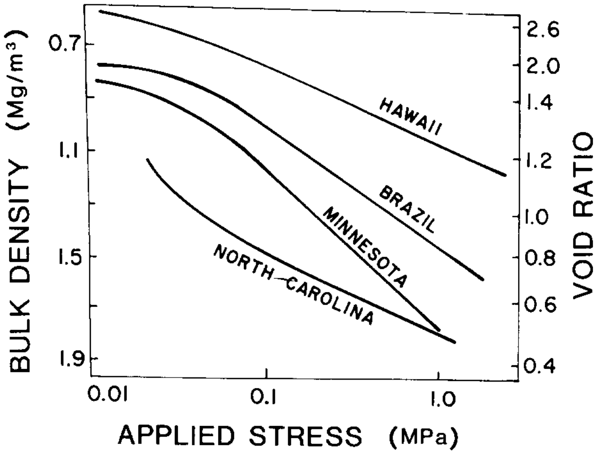

Fig. 1. Soil compression curves for world soils at pore water potential of −30 kPa (Larson et al., 1980).

clay and amount of organic matter. They also concluded that the more readily available uniaxial compression test (compared with triaxial) was satisfactory for this approximation. This accords with Koolen and Kuipers' (1983) conclusion that bulk density responded mainly to stress in the vertical direction.

Larson et al. (1980) also developed an equation to account for effects of water content on the virgin compression curves. Since virgin compression curve data are not always readily available (or obtainable), Gupta and Larson (1982) and Gupta et al. (1985) developed relationships between the compression and easily measurable soil properties such as particle size distribution. Using this approach, the predicted porosity vs. water content relationship for a sandy soil from Brazil was very close to the measured values (Fig. 2), but not very close for a clay loam soil from Minnesota (Fig. 3). The clay loam soil in Fig. 3 is a

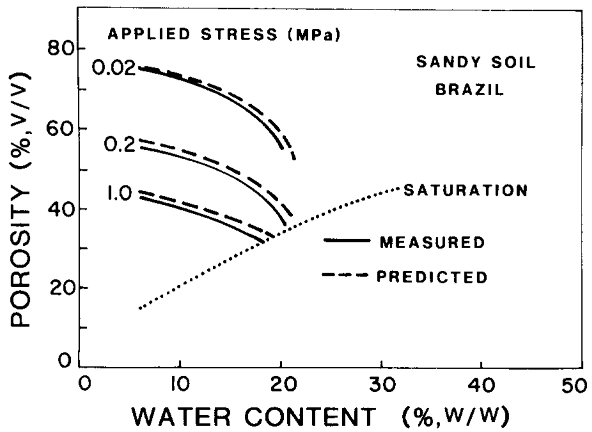

Fig. 2. Measured and predicted porosity vs. water content relationship of a sandy soil from Brazil at various applied stresses, σ_a (Gupta and Larson, 1982).

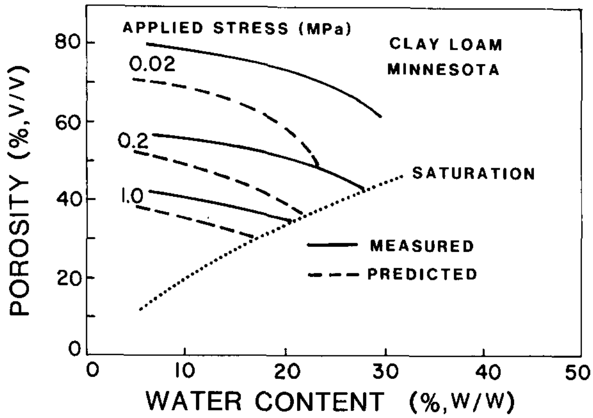

Fig. 3. Measured and predicted porosity vs. water content relationship of a clay loam soil from Minnesota at various applied stresses, σ_a (Gupta and Larson, 1982).

well-structured soil developed under moderately cool grassland vegetation, compared with the highly oxidized poorly structured soil from Brazil. This approach overestimated the amount of consolidation on the well-structured soil, and research is in progress to refine this approach to be more sensitive to soil structure.

In addition to a reduction in porosity, compactive forces can also increase penetrometer resistance. Gupta et al. (1985) used an approach similar to that given above to relate particle size and bulk density to penetrometer resistance in response to an applied load. These data can be used in addition to porosity reduction as an index of soil compactibility. Blackwell and Soane (1981) developed a method to predict bulk density by depth. Gupta and Allmaras (1986) discuss the need for, and progress in, defining the level of compaction in the whole rooting profile.

In the United States, the bulk of agricultural land has been surveyed, and particle size distribution data are available for literally thousands of soil types. It is the goal of the Soil Conservation Service to complete detailed soil surveys of all agricultural land, distinguishing soil areas as small as 0.5 ha. Such a detailed survey, with its particle size data, would easily allow individual farm fields, or portions of a field, to be arbitrarily classified according to their ease of consolidation or compactibility. Much of this information is currently computer accessible.

COMPACTION PROBABILITY

Assessment based only on the first step would allow one to state, for example, that Soil A is more easily consolidated than Soil B. Furthermore, the potential consolidation can be quantified in units of pore space or penetrometer resistance. If the soil in Fig. 3 had a water content of 20% (w/w) and was subjected to a compactive load of 0.2 MPa, the resulting total porosity is predicted to be about 40% (v/v) (corresponding to a bulk density of about 1.6 Mg m^{-3}). Based on this alone, it might be concluded that this particular soil should be classified as being quite susceptible to compaction. However, if this particular soil is always much drier than 20% (w/w) when compactive loads of 0.2 MPa are applied in the field, it should be concluded that it is susceptible to compaction but that the chances of compaction under field conditions are very small. This qualification puts that particular soil in a much less vulnerable category than originally concluded on the basis of isolated soil mechanical behavior alone.

To accomplish this second step requires 2 data bases: long-term weather and/or soil moisture data, and knowledge about the prevailing cultural practices for that particular soil. Long-term precipitation records are available for several sites within each state. Probabilities for a given amount of precipitation on a given date have been calculated (Feyerherm et al., 1966). Together with on-going soil moisture surveys conducted by various government agencies, it is possible to estimate the probability of a soil having a given water content on a given date. This phase can be further refined by incorporating knowledge concerning persistence of compaction as affected by wetting and drying cycles (Akram and Kemper, 1979) and freeezing and thawing (Voorhees, 1983; Benoit and Mostaghimi, 1986).

The second data base required is that of machinery characteristics for a given crop culture, i.e., data that would provide soil–tire contact pressures, axle load, wheel configuration, number of vehicular trips across the field, and average date for each field operation (related to probability of a certain soil water content). Sources for these data are available from agricultural engineering handbooks, farm management records, farm machinery industry, and State Extension personnel.

The end product of this step of the classification would allow a prediction, for example, that vehicular wheel traffic normal for growing maize on the Minnesota soil in Fig. 3 will impose maximum vertical loads of 0.2 MPa every year, and that in 8 out of 10 years the soil water content will be at least 25% (w/w) at the time this load is imposed, so that a 15% decrease of total porosity will result. Refinements in this approach would allow similar statements about penetrometer resistance, aggregate size, hydraulic conductivity, etc. Expressions of these changes by depth would also be desirable.

This classification scheme thus far would estimate the potential compactibility of a given soil over a range of water contents, and the probability of bringing about a certain change in soil physical properties based on prevailing cultural practices unique for that soil, crop and climate.

AGRO-ECONOMIC RESPONSE TO COMPACTION

Classification of soils for susceptibility to compaction implies that there must be some agriculturally important consequences of compacting a soil. This scheme proposes three areas of response: (i) agronomic effects; (ii) erosion; (iii) energy needs. Each of these response areas must have an economic value assigned to it, either an immediate value such as would accompany a crop yield loss, or a long-term value such as loss of productivity because of increased erosion. This phase of the classification is perhaps the most difficult, because it cannot be based on laboratory measurements, but must be based on results from either field experiments or observations, which are generally limited in number. Another factor making this a difficult step is the non-linear response to compaction. Each of the responses listed above will be discussed briefly to illustrate this point.

Agronomic effects

Early research concentrated on obvious compaction-related crop yield problems and tended to suggest that any reduction in bulk density would automatically increase crop yield. More recent research, however, has vividly demonstrated that for each crop, soil and season there is an optimum level of compaction for maximum crop yield (Soane, 1985). Compaction above or below this optimum will result in decreased yield. This is especially true for compaction within the surface 30 cm. Generally, a given degree of shallow compaction will be detrimental under wet climatic regimes and of no consequence, or even beneficial, under dry climatic regimes.

Wet and dry are relative terms, but they have been quantified for two crop species in Minnesota. Figure 4 shows the relative change in soya bean yield due to inter-row wheel traffic plotted against growing season precipitation from a 13-year field study. Wheel traffic each year consisted of three inter-row wheel passes of a tractor with an axle load of about 3 Mg before spring planting. If May–August precipitation was less than about 360 mm, soya bean yields were significantly increased by the presence of inter-row wheel track compaction. This yield increase appears to be due to better water conservation in moderately dry soil, and also to more phosphorus uptake with the higher volumetric water content of moderately compacted soil. When May–August precipitation exceeded 360 mm, soya bean yields were decreased by up to 20% by compaction, probably because of poor aeration.

Qualitatively similar results were obtained for wheat, as shown in Fig. 5, where the percentage change in wheat yield caused by spring-time pre-seeding wheel traffic is plotted as a function of growing season precipitation. When April–June precipitation was less than 200 mm, yield was dramatically increased by moderate compaction owing to better germination and early

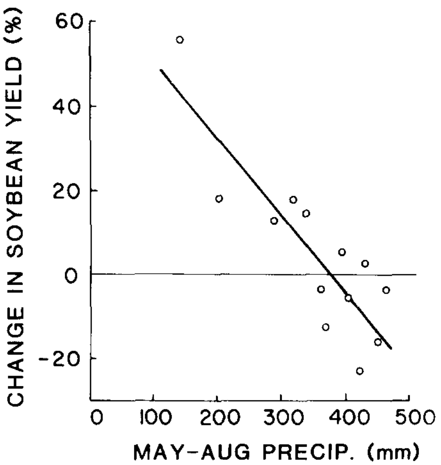

Fig. 4. Relative change in soya bean yield due to spring-time wheel traffic compaction as a function of growing season precipitation, 1973-1985 (Voorhees, 1986).

growth. When April–June precipitation exceeded 200 mm, yield was decreased by as much as 30%. In this study, wheat was seeded either directly into the wheel tracked soil or between the wheel tracks of a 3 Mg/axle tractor.

In both of the above examples, bulk density at the time of spring wheel traffic did not vary widely from year to year; the major soil moisture differences occurred after planting and thus the yields more closely reflected growing season conditions. Total precipitation is an oversimplified way to characterize climate because it says nothing about the distribution of the rainfall during critical growth periods such as flowering; nor does it take into account initial soil water content at the beginning of the season. Nevertheless, it does provide

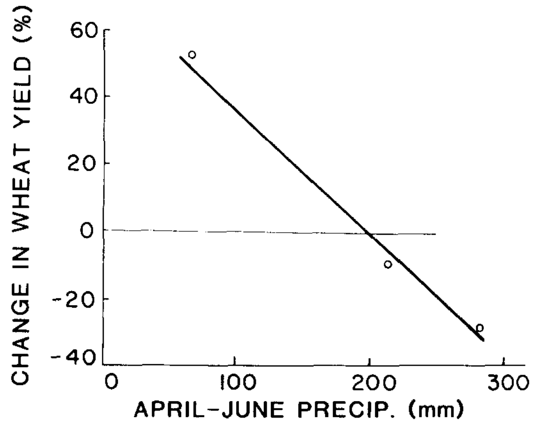

Fig. 5. Relative change in wheat yield due to spring-time wheel traffic compaction as a function of growing season precipitation, 1973-1975 (Voorhees et al., 1985a).

a starting point from which to quantify plant response to surface compaction and climate for a given soil. Similar analogs may be forthcoming from an international study on subsoil compaction (Håkansson et al., 1986).

Erosion

The most obvious effect of wheel traffic compaction on the erosion process is a reduction in infiltration rates leading to increased water runoff and soil erosion. This has been documented and quantified for a few soils in Minnesota (Lindstrom and Voorhees, 1980; Lindstrom et al., 1981; Young and Voorhees, 1982). However, there are some beneficial aspects of compaction. Soils that are normally tilled in the autumn will have a very rough cloddy surface structure if the soil had been previously compacted, and this can offer a degree of erosion control during the off-season when the soil is normally bare and unprotected (Voorhees et al., 1979). The economic value of the loss of a thin layer of topsoil or a few cm of water is difficult to judge. However, models exist, such as the Productivity Index (Pierce et al., 1983), that allow a first approximation of the economic value of erosion. Holt et al. (1964) showed that an extra 2.5 cm of water stored in the soil has the potential to increase maize yield by about 600 kg ha^{-1}.

Energy needs

The primary concern here is the increased energy required to till a soil that has been compacted. In this area, there are probably more data available than for the other two areas of response, although they may not be in the desired form. Voorhees (1979) related wheel traffic compaction to increased tillage energy requirements, but also recognized some beneficial aspects of moderate compaction in terms of reduced wheel slip. Taylor (1985) pointed out the advantage of a firm soil not only in terms of trafficability and fuel economy, but also in timeliness of field operations. Several monographs are available to estimate tillage energy based on soil properties (Anon., 1983).

CONCLUSIONS

When the above three consequences of compaction (agronomic effects, erosion, energy needs) are considered in total, a net economic value can be assigned. The concluding predictive example given in the Compaction Probability section can then be extended as follows: vehicular wheel traffic normal for growing maize on the Minnesota soil in Fig. 3 would impose maximum vertical loads of 0.2 MPa every year, and in 8 out of 10 years the soil water content will be at least 25% (w/w) at the time this load is imposed, which will result in a decrease of total porosity from 55 to 40% (v/v), corresponding to a bulk density increase from 1.2 to 1.6 Mg m^{-3}. As a result, maize grain yields will be decreased by 300 kg ha^{-1} and fossil fuel requirements will be increased by 10 l ha^{-1}. The net monetary loss as a consequence of this compaction would be U.S. $22 ha^{-1} (absolute numbers are used for illustration purposes only).

In summary, this classification scheme uses basic principles of soil mechanics, soil survey data, long-term weather records, field research results and a general knowledge of prevailing cultural practices to assess the overall agro-economic consequences of soil compaction. It can be used to identify where changes need to be made in terms of machinery management to avoid later detrimental consequences. This scheme can also be used to identify research gaps, and suggest areas of concern where practical agriculture and pedotechnology need to make a concerted effort to work more closely.

This classification scheme is at present in a skeletal form, but offers an overall systematic approach using currently available large soil and climate data bases. Work is in progress to refine and extend various segments so that it can be field tested initially for a land area of approximately 2 million ha.

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